



## **Airflow Characteristics at the Breathing Zone of a Seated Person**

Passive Control over the Interaction of the Free Convection Flow and Locally Applied Airflow from Front for Personalized Ventilation Application

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# **AIRFLOW CHARACTERISTICS AT THE BREATHING ZONE OF A SEATED PERSON: PASSIVE CONTROL OVER THE INTERACTION OF THE FREE CONVECTION FLOW AND LOCALLY APPLIED AIRFLOW FROM FRONT FOR PERSONALIZED VENTILATION APPLICATION**

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## **Abstract**

A workstation with a desk-mounted Personalized Ventilation (PV) unit, with circular diffuser ( $d = 0.185$  m) supplying air from the front/above towards the face of a thermal manikin with realistic body shape and temperature distribution was set in a climate chamber ( $4.70$  m x  $1.62$  m x  $2.6$  m). The distance between manikin's face and the diffuser was  $0.4$  m. Mixing overhead ventilation at  $15$  L/s was used to ventilate the chamber. The room air temperature was kept at  $20$  °C. The PV air was supplied isothermally at  $4$ ,  $6$  or  $8$  L/s. The thermal manikin was sitting  $0.1$  m away from the front edge of the table. Passive method for control over the airflow characteristics at the breathing zone to increase the amount of clean air in inhalation consisted of a rectangular board ( $0.63$  m x  $0.36$  m) placed below the table and pressed against the abdominal. It acted as a barrier reducing the convection flow upcoming from the lower body. The resultant velocity field at the breathing zone was measured with Particle Image Velocimetry: a dual cavity laser ( $\lambda = 532$  nm) and two CCD cameras with  $35$  and  $60$  mm lenses. Seeding consisting of glycerol droplets ( $d = 2\text{-}3$   $\mu\text{m}$ ) was added to the total volume supply. The blocking of the convection layer by the board decreased twice the absolute mean velocity at the mouth: from  $0.2$  m/s to  $0.1$  m/s. This made it possible for the PV flow already at  $4$  L/s to penetrate the free convection flow, which without the board was achieved at the PV flow rate of  $6$  L/s.

**Keywords:** convection flow, personalized ventilation, passive control, airflow interaction

## **Introduction**

In calm indoor environment ( $v < 0.1$  m/s) a convective boundary layer is developed around the human body for the surface temperature of the body is different to that of the surrounding air temperature. In the range of comfortable room air temperatures, it starts at the feet and close to the floor. About  $1$  m height from the floor the boundary layer transforms from laminar to turbulent and above  $1.5$  m (mid-chest) it becomes fully turbulent (Clark and de Calcina-Goff 2009). A standing subject at  $20$  °C room temperature can generate a thermal plume with flow rate of up to  $60$  L/s with a maximum velocity of  $0.25$  m/s above the head (Clark 1976, Homma and Yakiyama 1988). Thus the velocities measured within the convective flow are close to the upper limits of room air velocity ( $0.2$  m/s) suggested in the existing guidelines and standards (CEN CR 1752-1998, EN 15251-2007). Thus the free convection boundary layer affects significantly the airflow interaction at the breathing zone, the thermal (convective) plume above the body and the resultant air-flow pattern in occupied spaces (Zukowska et al. 2008).

Personalized Ventilation (PV) is used to provide clean air close to the breathing zone of each occupant, and thus to improve the perceived air quality (Melikov 2004). The PV is usually a free jet that is supplied and directed towards the breathing zone of the individual. The closer to the face the PV air supply unit is, the less mixing of the personalised air with the polluted room air and the better

inhaled air quality and protection from airborne diseases it will provide. However, on the other hand, in order to avoid the risk from draft the velocities should be kept low. The direction of the PV flow (transverse, assisting or opposing to the boundary layer at the breathing zone) is another important factor affecting the airflow interaction at the breathing zone and thus the effectiveness in supplying the clean PV air for breathing. Transverse/opposing PV flow, i.e. normal to or counteracting the boundary layer flow direction, would require much more initial momentum to penetrate and overcome the free convection flow compared to the flow supplied from below (assisting).

Under normal indoor conditions (air temperature within 20 to 26°C) high target velocity (over 0.25 m/s) is needed for the clean PV air supplied from front to penetrate the boundary layer. One way to reduce the target velocity needed for penetration is to decrease the strength of the boundary layer at the face so that more personalized clean air can reach the breathing zone of the individual. This strategy is advantageous to the strategy of increasing the PV flow rate. The weakened convective layer would be easily penetrated by the personalized flow at a reduced target velocity (below 0.25 m/s), i.e., at a reduced personalized supply flow rate resulting in an improved local thermal sensation (reduced draught), eyes sensitisation (dry eyes) and decreased energy consumption. Bolashikov et al. (2009) showed that placing a board below the table tightly fitted to the groins of a seated occupant serves as an effective barrier for the convection flow coming from the legs, and results in increased amount of clean PV air into inhalation. The personalised air was supplied from the front against the face from a circular air supply diffuser (Bolashikov et al. 2003). The performance of the PV at 6 L/s supply flow rate and with the board was comparable and even better than the case when no control over the convection layer was used and the PV was operated at 8 L/s. However to explore better the possibilities of such passive control strategy (no energy is used to operate the board), better understanding of the flow interaction at the breathing zone is needed.

The current paper presents Particle Image Velocimetry measurements of the airflow characteristics at the breathing zone, when the passive control method over the boundary layer and a personalised flow supplied from the front were applied.

## Methods

The experiment was designed and performed in a full-scale test room with dimensions 4.70 m × 1.62 m × 2.60 m (W×L×H). Three ceiling-mounted light fixtures (6 W each) provided the background lighting. A workplace consisting of a desk with a seated breathing thermal manikin, an ordinary light office chair and a desk-mounted personalized ventilation device that generated the personalized jet were used in the experimental set-up (Figure 1).

The thermal manikin with body shape and size of an average Scandinavian woman of 1.7 m height was used to resemble a seated occupant. The surface temperature of the thermal manikin was controlled to simulate a person in a state of thermal comfort at light sedentary activity and to realistically recreate the existing around the body convective boundary layer. During all measurements the breathing option was disabled.

The PV unit used to supply the air jet frontally during the measurements was with circular supply opening, named Round Movable Panel (RMP) with a diameter  $d = 0.18$  m, was mounted on a lamp like support (Bolashikov et al. 2003) and attached to the desk. The diffuser was positioned at a distance 0.4 m from the face and supplied the personalized flow from front/above (at 40°) centring the nose and mouth facial area of the manikin. During the measurements the manikin was placed 0.10 m away from the front table edge.

A plastic impregnated cardboard piece with rectangular shape was used as a passive means to reduce the strength of the convection layer surrounding the manikin. The board was placed in front of the thermal manikin to block the gap between the abdomen and the front edge of the desk (0.10 m), and thus to prevent the warm air generated by the lower body parts, i.e. feet, legs, thighs, from moving upwards towards the breathing zone.

The test room itself was built in a laboratory hall, 0.7 m above the floor. The laboratory hall had a separate ventilation system allowing for temperature control. The air temperature of the laboratory hall was kept at the same level as in the test room.

Mixing type ventilation was used to condition the air in the test room. The air supply diffuser (a swirl diffuser) and the air exhaust diffuser (a perforated circular diffuser) were installed on the ceiling (Figure 1). The supplied air was 100% outdoor air (no recirculation was used) with a flow rate of 15 L/s, which corresponded to an air change rate of  $2.7 \text{ h}^{-1}$ . A slight under-pressure of  $1.4 \pm 0.1 \text{ Pa}$ , resulting in 30 L/s at the exhaust, was kept during all the experimental conditions in order to avoid a flow of air from the test room to the surroundings and pollute with seeding the environment. The air temperature in the chamber and the surroundings was kept at  $20^\circ\text{C}$ .

The PIV equipment included a double cavity New Wave Solo 120XT Nd-YAG laser (wavelength 532 nm), capable of delivering light pulses of 120 mJ. However the light pulses emitted were up to 60% of the maximal value. The pulse width, i.e. the duration of each illumination pulse, was 10 ns. The light sheet thickness at the measurement position was 2 mm. The laser was placed frontally, illuminating the face of the thermal manikin from the front and along the axis bisecting the body in two symmetric halves. Two Dantec Dynamics Hi Sense MkII CCD cameras (1344×1024 pixels) equipped with 35 mm and 60 mm lenses and filters that only pass light with wavelengths close to that of the laser light were placed on the same side of the light sheet next to each other. In the present paper only the results for the 35 mm lenses camera are reported. The f-numbers (the focal length divided by the "effective" aperture diameter) were set to values between 4 and 5.6 to control the light budget of the particle scattering and reflections from the face of the breathing thermal manikin.

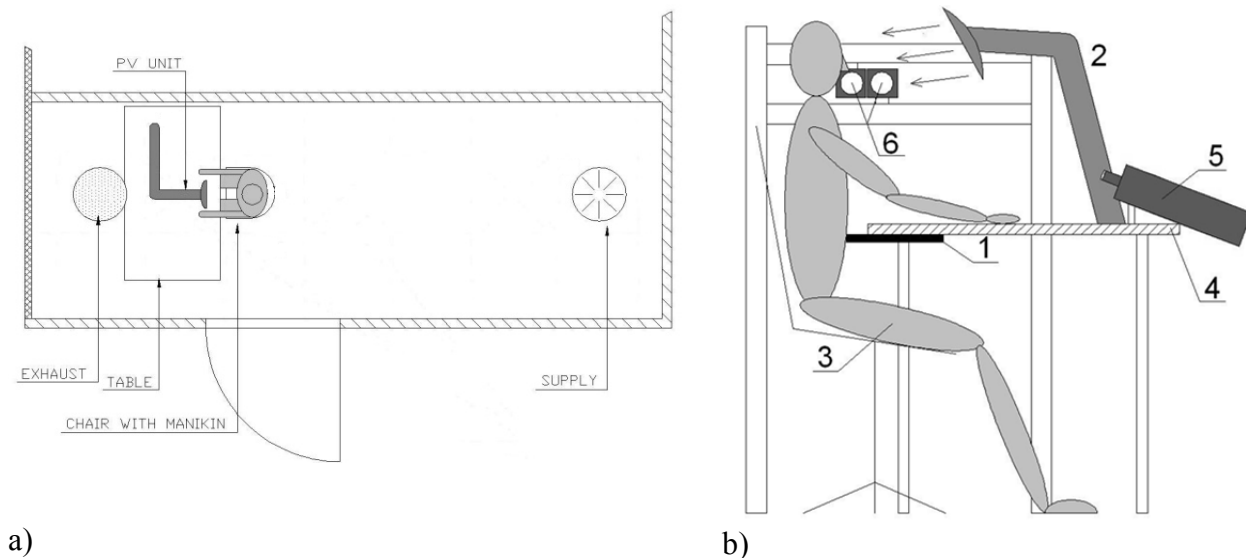


Figure 1 PIV set-up in the experiment with the RMP: a) chamber set-up and b) closer side view. 1) passive control method – straight board, 2) RMP, 3) thermal manikin, 4) table, 5) laser generator, 6) CCD cameras.

Seeding consisting of glycerol droplets with a diameter of  $2\text{--}3 \mu\text{m}$  was added to the supplied total ventilation air flow (mixture of water and pure glycerol in volume parts 0.7 to 0.3). The seed particles were added before the supply air mixing box in order to obtain a more homogeneous distribution of the tracers in the supplied background ventilation flow.

In all studied cases with the RMP the supplied air was taken from the test room, i.e. room air with seeding was supplied as a personalised air. Voltage controlled duct fan was used to achieve the needed flow rate of personalised air supplied from the RMP.

The images were processed using Dantec Flow Manager © software version 4.7. For each measurement case 1000 realizations were acquired. The recording of image maps was done with time between pulses and trigger rate dependent on the PV flow rate supplied by the RMP from 2 700 to 12 000  $\mu\text{s}$  and from 0.2 to 2 Hz respectively. The largest time separation between pulses corresponds to

the cases when only the convective flow was measured and the smallest ones to the case of PV at 8 L/s.

Reflections from the face of the breathing thermal manikin entering the CCD cameras constituted a problem for two reasons. The reflections appeared along the profile of the face in the part of the measurement region, corrupting the signal in this area. Strong reflections may cause damage to the camera CCD chip. Unwanted reflections were suppressed by applying a paper tape strip along the reflecting surfaces painted with a mixture of Rhodamine 6G and black non-shiny paint. Rhodamine 6G is a fluorescent dye, absorbing light with the wavelength of the laser and reflecting light which has a wavelength slightly shifted from the absorbed one. Additionally, the cameras were equipped with green-pass filters, which only permitted the wavelengths of the laser to pass. In this way, hazardous reflections were substantially reduced.

## Results

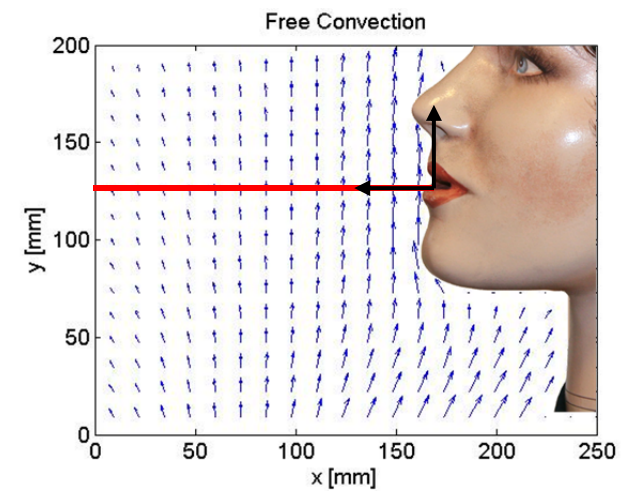
In Figure 2 the vector plots of the averaged velocity within the x, y plane normal to the face and bisecting the body of the thermal manikin are presented. Figure 3 displays the velocity profile plots of the mean absolute velocity downstream the centre of the mouth opening within the same x-y plane. The origin of the local Cartesian coordinate system is positioned at the geometrical centre of the mouth (Figure 2a), with positive y directed upwards and positive x directed outwards from mouth. The negative sign of the scalar shows the dominating direction of the vector component within the plane it was measured, i.e., positive shows that it is directed upwards (assisting the convection layer), negative: it is directed transverse or is opposing the convection flow. The absolute mean velocity within the x-y plane is given as:

$$\bar{v} = \sqrt{\bar{v}_x^2 + \bar{v}_y^2}, \text{ where}$$

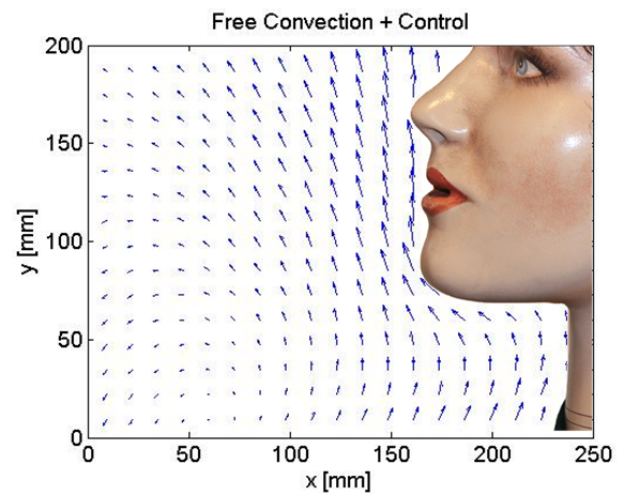
$$\begin{aligned} \bar{v}, & \quad \text{mean absolute velocity value;} \\ \bar{v}_x, & \quad \text{the component of the mean velocity along the x axis;} \\ \bar{v}_y, & \quad \text{the component of the mean velocity along the y axis.} \end{aligned}$$

Figures 2a and 2b show the vector plot when no flow was supplied from front without (Figure 2a) or with (Figure 2b) the board attached below the table and pressing against the stomach of the thermal manikin. The presence of the board reduced the strength of the free convection layer at the face. The maximum absolute mean velocity measured within the convection layer and across from the mouth dropped from 0.19 m/s without the board to 0.10 m/s with the board (Figures 3a, 3b). When the board was not used, the absolute mean velocity in the boundary layer was 0.10 m/s at 0.06 m from the mouth (Figure 3a). The same velocity of 0.10 m/s was measured at 0.0085 m in the case when the board was used (Figure 3b).

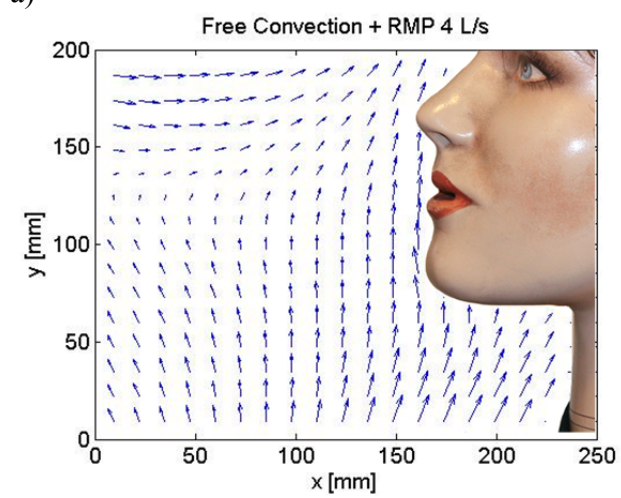
The velocity magnitude at the face region when the PV flow was directed from the front depended on the amount of air supplied. In the case when the board was not used the 4 L/s frontally supplied air flow was not strong enough to penetrate the boundary layer. Instead the PV air pushed the boundary layer closer to the face and was then deflected upwards and away from the breathing zone (Figure 2 c). At 6 L/s and 8 L/s the air supplied from the front managed to penetrate the boundary layer (Figures 2e, 2g). However at 8 L/s the frontally provided flow spread better and covered the whole face compared to the case when at 6 L/s, Figure 2g. At 6 L/s the mouth of the manikin was closer to the region of interaction between the two flows, Figure 2e.



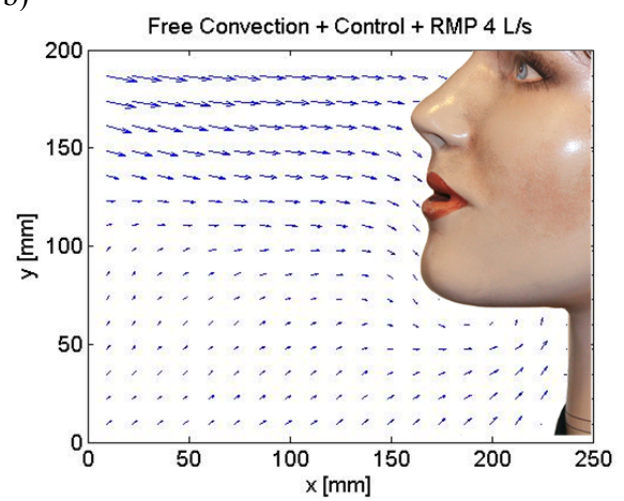
a)



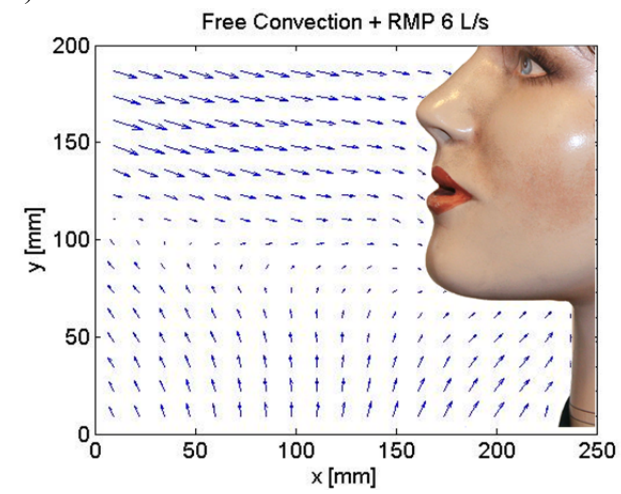
b)



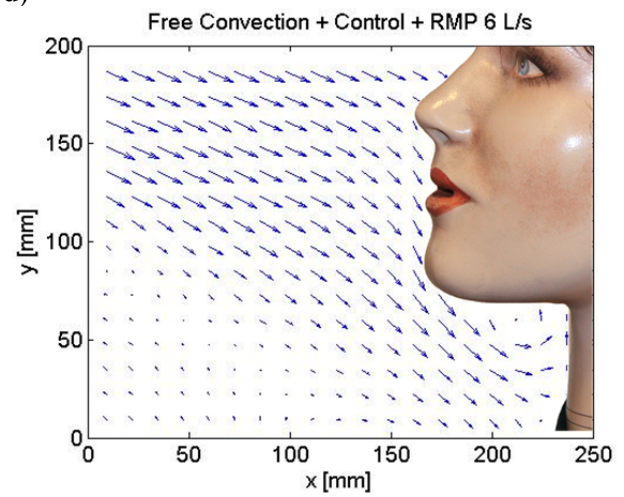
c)



d)



e)



f)



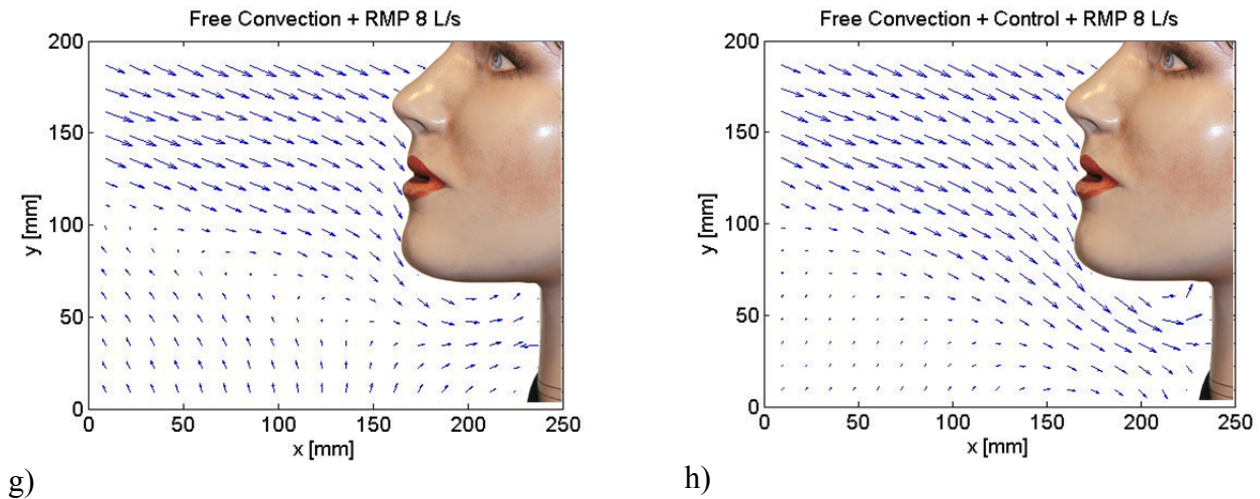


Figure 2. Contour plots of mean velocity magnitude measured with the PIV technique as a result of the flow interaction at the face of the breathing thermal manikin when a) convection flow was not controlled and no PV flow from front, b) the passive control method was used and no PV flow from front, c) convection flow interacts with PV flow of 4 L/s, d) convection flow is controlled and PV flow of 4 L/s is supplied frontally, e) convection flow interacts with PV flow of 6 L/s, f) convection flow is controlled and PV flow of 6 L/s is supplied frontally, g) convection flow interacts with PV flow of 8 L/s, h) convection flow is controlled and PV flow of 8 L/s is supplied frontally.

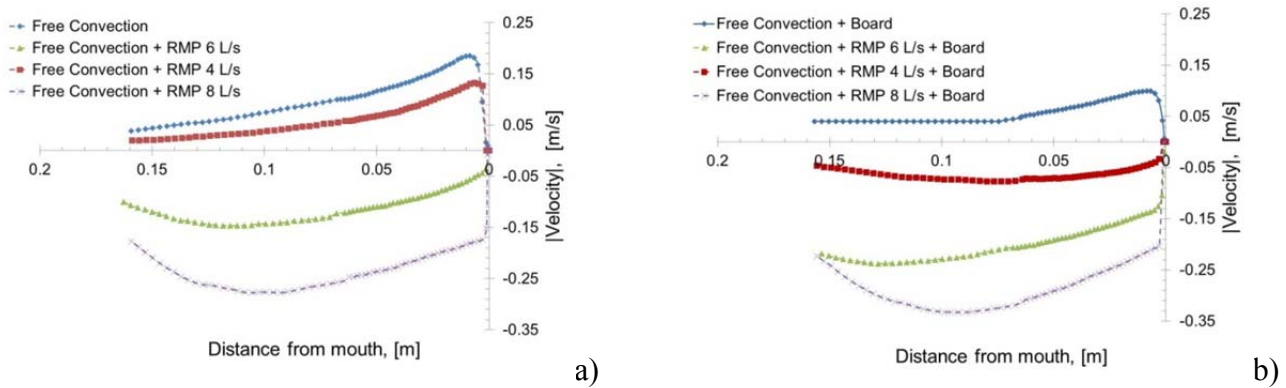


Figure 3. Absolute mean velocity magnitude presented downstream the middle section of the mouth within the  $x$ - $y$  measurement plane a) when no control over the convection was applied, b) when control over the convection flow was applied.

The positioning of the board at the groins, closing the gap between the manikin and the table resulted in elevated velocities at the face compared to the case when no control was used at all three flow rates tested (Figure 3). Already at 4 L/s the flow from the front was able to push away the boundary layer and dominate in the flow interaction (Figure 2c) resembling the flow interaction when no control and RMP was supplying 6 L/s (Figure 2e). When the PV flow was increased to 6 L/s and with the board, the vector plot of the velocity resembled that at 8 L/s and no control (Figures 2f, 2g). With the board installed below the desk the vector plots at 6 and 8 L/s look identical (Figures 2f, 2h). The difference is noticed only in the mean absolute velocity within the  $x$ - $y$  plane changing from 0.24 at 6 L/s to 0.33 m/s at 8 L/s (Figure 3).

Breathing is a transient flow process that also needs to be considered when studying the flow interaction characteristics near the face of the occupants. This however needs to be further studied when used with the reported here passive control method over the boundary layer.

## Discussion

All the results obtained in the present study suggest that better understanding of the flow interaction is important in order to fully benefit from the clean personalised air directed towards the

breathing zone of an occupant. Instead of supplying more air to achieve the penetration of the boundary layer by the PV flow, one can think of a way to control the flow interaction so that more clean air ends up in inhalation at lower PV flow rate. This can eventually lead to a substantial decrease in the PV flow rates and enhanced performance with respect to air quality. It is important to extend the first region of the jet (the potential core) providing the clean air (near the nozzle opening) to be prolonged as much as possible so that the clean air is inhaled before mixing with the polluted surrounding air. Increasing the initial velocity is not very energy efficient as increased velocity translates into increased volume of air. Hence additional expenses are also implied: more powerful fans, larger ducts, higher demand for heating or cooling of the PV air, depending on the season and temperature difference between the PV air and the room air. Therefore the control over the PV flow should be done meaningfully and should result in lowered energy consumption. At the same time the air quality performance and individual protection of occupants from airborne diseases should not suffer or be reduced. It is also important that the targeted area by the clean personalized air, i.e. the area where the face is located, is large enough to accommodate moderate head movement. Therefore PV nozzles with a relatively large area are recommended for use in practice. However, when large nozzles are used, a high personalized flow rate is needed in order to ensure the minimum velocity needed for penetration of the convective flow. This leads again to the topic of energy consumption. Another concern is that the relatively high velocity needed for penetration of the convection flow (above 0.25 m/s) may cause draught discomfort to the PV users, especially at the winter range of room air temperature (20 - 23 °C) recommended in the standards. The problem to be solved is to ensure a relatively large target area of clean air at the breathing zone at a reduced flow rate of personalized air, i.e. with as much lowered as possible penetration (target) air velocity so that even the most sensitive people to feel comfortable and satisfied. In order to solve the problem, control of the airflow interaction at the breathing zone, especially control and weakening the strength of the free convection flow, becomes essential. The utilisation of control over the convection flow will bring also energy savings and make the PV more attractive for future building investments. However this topic needs to be further investigated.

The present article looks into the utilisation of passive methods as possible flow interaction control. Melikov et al. (2011) explores the applicability of a suction box installed under the desktop to thin out the free convection layer. With respect to air flow interaction the performance of this active control method is very much similar to that of the passive one investigated here. The energy penalties associated with the latter (active) method are not so high (1.4 W computer fans) and can be justifiable especially in cases when the passive method (blocking board) causes discomfort issues to the final users.

A mere physical barrier on the upward way of the free convective layer (Figure 2) already results in penetration of the boundary layer at reduced flow rate of the PV flow supplied from front: the penetration is realised already at 4 L/s, an amount that is recommended as lowest per person in the present standard EN 15251 (2007). The aim of this barrier was to avoid the growth and thickening of the free convective layer in front of the body of a seated occupant as a result of joining of the convective flow originating at the feet and the one starting at the groins (Homma and Yakiyama 1988, Zukowska et al. 2007). Blocking the free convective layer results in more than 93% of clean air into the inhalation zone of the occupant (Bolashikov et al. 2009) at 6 L/s (0.23 m/s target velocity, Figures 3c, 3d), an amount earlier achievable only at flow rates above 12 L/s (Bolashikov et al. 2003). Furthermore it would prevent the pathogen laden airborne particles and odorous substances to be moved upwards from the lower room levels via entrainment towards the breathing zone which would eventually happen provided a gap exists between the body and the desktop.

Another benefit of the passive control method is the possibility to reduce the supplied flow without affecting the air quality but reduce the air movement at the face, to which certain people are sensitive and find it unpleasant, i.e. people with optical lenses.

A board installed below the desk top panel and pressed gently against the occupant's abdomen with a simple spring mechanism can be easily and aesthetically applied in practice. The board will



follow the backward and forward body movement and thus will break the free convection flow and will improve the performance of PV providing air at a low flow rate. Furthermore Bolashikov et al. (2009) showed also that the shape of the board (straight edge or shaped to fit tighter to the abdomen) is not important for the performance of the control method with respect to the amount of PV air inhaled by the occupant.

## Conclusions

Based on the performed measurements the following conclusions can be drawn:

The blocking of the convection layer by the board decreased twice the absolute mean velocity at the mouth: from 0.2 m/s to 0.1 m/s.

The weakening of the free convection flow in front of the manikin's body by the board made it possible for the PV flow already at 4 L/s to penetrate the free convection flow, which without the board was achieved PV flow rate of 6 L/s.

## Acknowledgements

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